

WHAT IS CLAIMED IS:

1. A variable capacitor device comprising:  
a first multi-layered substrate formed from a low-temperature, co-fired ceramic (LTCC) material,  
a microelectromechanical device microfabricated on the a first substrate, the microelectromechanical device comprising a variable capacitor, and  
a second multi-layered substrate formed from the LTCC material, a portion of the second substrate being removed to form a cavity therein,  
the first and second substrates being bonded together to enclose the microelectromechanical device,  
the microelectromechanical device being electrostatically actuated, wherein the capacitance of the device is controlled by a DC voltage applied to the device.
2. The variable capacitor device of claim 1, wherein the microelectromechanical device includes upper and lower electrodes, and wherein the DC voltage applied to the upper and lower electrodes controls the capacitance between the electrodes.
3. The variable capacitor device of claim 2, wherein the shape of the upper and lower electrodes, in addition to the applied DC voltage, controls the capacitance between the electrodes.
4. The variable capacitor device of claim 1, wherein the cavity enclosed in the first and second substrates bonded together contains a partial vacuum or an inert ambient gas to facilitate the operation and reliability of the microelectromechanical device.
5. The variable capacitor device of claim 1, wherein the first and second substrates include continuous electrical connections through their respective layers.
6. The variable capacitor device of claim 1, wherein the LTCC material has low resistive losses at frequencies above 30 GHz.

7. The variable capacitor device of claim 1, wherein the device is electronically tunable to a selected value and wherein a predetermined actuation voltage is applied to the upper and lower electrodes to maintain the capacitor device at the selected value.

8. The variable capacitor device of claim 1 further comprising a third substrate bonded to the second substrate, the third substrate including an integrated circuit flip-chip bonded onto electrical bonding pads fabricated onto the surface of the third substrate, the integrated circuit sensing and measuring the capacitance value of the variable capacitor and apply suitable actuation voltages to the device actuation electrodes to keep the capacitance of the device actively adjusted to the selected value.

9. The variable capacitor device of claim 1, wherein thin-films of materials are deposited, patterned and etched on the surface of the first substrate to form the microelectromechanical device.

10. The variable capacitor device of claim 1, wherein each LTCC substrate layer includes means for incorporating electrical connections and interconnections, through wafer vias, discrete components, sealable cavities, and bonded integrated circuits.

11. The variable capacitor device of claim 1, wherein the LTCC material has a low loss tangent and a high k factor value for high performance, high-frequency applications.

12. The variable capacitor device of claim 2, wherein the variable capacitor is tuned to a selected value and a short, low-voltage, high-current pulse of sufficient duration to essentially “weld” the electrodes together at the selected capacitance value is applied.

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13. The variable capacitor device of claim 2, wherein a substantially fast curing polymer material is applied to the electrodes to affix them at a desired position whereby the device is locked in to a tuned capacitance value.

14. The variable capacitor device of claim 2, wherein the electrodes are welded by a high-powered laser to a tuned position whereby the device is locked into a selected capacitance value.

15. The variable capacitor device of claim 1, wherein the first and second substrates are bonded together using eutectic bonding.

16. The variable capacitor device of claim 1, wherein the first and second substrates are bonded together using a glass-frit technique.

17. The variable capacitor device of claim 1, wherein the first and second substrates are bonded together using a thermosetting polymer technique.

18. The variable capacitor device of claim 1, wherein the cavity provides a low-pressure, low humidity environment for the microelectromechanical device.

19. The variable capacitor device of claim 1, wherein a surface of the first LTCC substrate on which the microelectromechanical device is formed is micromachined to be smooth and uniform.

20. The variable capacitor device of claim 19, wherein the surface of the first LTCC substrate is micromachined by planarizing

21. The variable capacitor device of claim 19, wherein the surface of the first LTCC substrate is micromachined by polishing.

22. The variable capacitor device of claim 1, wherein the thin-film materials are selected from the group consisting of gold, silver, platinum, and/or aluminum.

23. The variable capacitor device of claim 1, wherein the LTCC material has a dielectric constant of ( $\epsilon_r$ ) is 7.5 +/- 0.1 and a loss tangent is 0.001.

24. A variable capacitor device comprising:

- a first multi-layered substrate formed from a low-temperature co-fired ceramic (LTCC) material,
- a microelectromechanical device microfabricated the first substrate and comprising a variable capacitor, the microelectromechanical device including:
  - a fixed electrode,
  - a movable electrode electrostatically actuated by a DC voltage applied to the movable electrode to vary the capacitance between the movable electrode and the fixed electrode, and
  - a mechanical stop to prevent the movable electrode from contacting the fixed electrode when the movable electrode is actuated, wherein an increased amount of area of the movable electrode is brought into contact with the mechanical stop in a zipper-like motion as the applied DC voltage is increased, whereby the capacitance between the movable electrode and the fixed electrode is varied as the amount of area of the movable electrode contacting the mechanical stop is varied, and
- a second multi-layered substrate formed from the LTCC material, a portion of the second substrate being removed to form a cavity therein,
- the first and second substrates being bonded together to enclose the microelectromechanical device.

25. The variable capacitor device of claim 24, wherein an increased amount of area of the movable electrode is brought into contact with the mechanical stop in a zipper-like motion as the applied DC voltage is increased, whereby the capacitance between the movable electrode and the fixed electrode is varied as the amount of area of the movable electrode contacting the mechanical stop is varied.

26. The variable capacitor device of claim 24, wherein the shape of the movable and fixed electrodes controls the capacitance between said electrodes.

27. The variable capacitor device of claim 24, wherein the geometry of each of the movable and fixed electrodes determines the relationship between the capacitance

between the movable and fixed electrodes and the DC voltage applied to said electrodes.

28. The variable capacitor device of claim 24, wherein a selected portion of the center area of the fixed electrode is removed to match the leveraging of the movable electrode to a non-linear relationship between the applied DC voltage and electrostatic force actuating the movable electrode to achieve a substantially linear relationship between the capacitance between the movable and fixed electrodes and the DC voltage applied to said electrodes.

29. The variable capacitor device of claim 24, wherein the device has a tuning ratio in excess of 100 with an applied actuation voltage of substantially less than 50V.

30. The variable capacitor device of claim 24, wherein the applied DC voltage controls the capacitance between the electrodes.

31. The variable capacitor device of claim 24, wherein the shape of the movable and fixed electrodes, in addition to the applied DC voltage, controls the capacitance between the electrodes.

32. The variable capacitor device of claim 24, wherein the cavity enclosed in the first and second substrates bonded together contains a partial vacuum or an inert ambient gas to facilitate the operation and reliability of the microelectromechanical device.

33. The variable capacitor device of claim 24, wherein the first and second substrates include continuous electrical connections through their respective layers.

34. The variable capacitor device of claim 24, wherein the LTCC material has low resistive losses at frequencies above 30 GHz.

35. The variable capacitor device of claim 24, wherein the device is electronically tunable to a selected value and wherein a predetermined actuation voltage is applied to the movable and fixed electrodes to maintain the capacitor device at the selected value.

36. The variable capacitor device of claim 24 further comprising a third substrate bonded to the second substrate, the third substrate including an integrated circuit flip-chip bonded onto electrical bonding pads fabricated onto the surface of the third substrate, the integrated circuit sensing and measuring the capacitance value of the variable capacitor and apply suitable actuation voltages to the device actuation electrodes to keep the capacitance of the device actively adjusted to the selected value.

37. The variable capacitor device of claim 24, wherein thin-films of materials are deposited, patterned and etched on the surface of the first substrate to form the microelectromechanical device.

38. The variable capacitor device of claim 24, wherein each LTCC substrate layer includes means for incorporating electrical connections and interconnections, through wafer vias, discrete components, sealable cavities, and bonded integrated circuits.

39. The variable capacitor device of claim 24, wherein the LTCC material has a low loss tangent and a high k factor value for high performance, high-frequency applications.

40. The variable capacitor device of claim 24, wherein the variable capacitor is tuned to a selected value and a short, low-voltage, high-current pulse of sufficient duration to essentially “weld” the electrodes together at the selected capacitance value is applied.

41. The variable capacitor device of claim 24, wherein a substantially fast curing polymer material is applied to the electrodes to affix them at a desired position whereby the device is locked in to a tuned capacitance value.

42. The variable capacitor device of claim 25, wherein the electrodes are welded by a high-powered laser to a tuned position whereby the device is locked into a selected capacitance value.

43. The variable capacitor device of claim 24, wherein the first and second substrates are bonded together using eutectic bonding.

44. The variable capacitor device of claim 24, wherein the first and second substrates are bonded together using a glass-frit technique.

45. The variable capacitor device of claim 24, wherein the first and second substrates are bonded together using a thermosetting polymer technique.

46. The variable capacitor device of claim 24, wherein the cavity provides a low-pressure, low humidity environment for the microelectromechanical device.



47. The variable capacitor device of claim 24, wherein a surface of the first LTCC substrate on which the microelectromechanical device is formed is micromachined to be smooth and uniform.

48. The variable capacitor device of claim 47, wherein the surface of the first LTCC substrate is micromachined by planarizing

49. The variable capacitor device of claim 47, wherein the surface of the first LTCC substrate is micromachined by polishing.

50. The variable capacitor device of claim 24, wherein the thin-film materials are selected from the group consisting of gold, silver, platinum, and/or aluminum.

51. The variable capacitor device of claim 24, wherein the LTCC material has a dielectric constant of ( $\epsilon\epsilon_r$ ) is 7.5 +/- 0.1 and a loss tangent is 0.001.

52. The variable capacitor device of claim 24, wherein the movable electrode is cantilevered.

53. The variable capacitor device of claim 24, wherein the mechanical stop is mounted on the fixed electrode.

54. A variable capacitor device comprising:  
microelectromechanical means for providing a variable capacitance,  
means for supporting the variable capacitance means, and  
means for enclosing in a cavity the variable capacitance means,  
the supporting means and the enclosing means each being formed from a plurality of layers of low-temperature, co-fired ceramic ("LTCC") material and being bonded together,

the variable capacitance means being electrostatically actuated by an applied DC voltage to control the variable capacitance.

55. The variable capacitor device of claim 54, wherein the variable capacitance means includes movable and fixed electrodes, and wherein the DC voltage applied to the electrodes controls the capacitance between the electrodes.

56. The variable capacitor device of claim 55, wherein the shape of the movable and fixed electrodes, in addition to the applied DC voltage, controls the capacitance between the electrodes.

57. The variable capacitor device of claim 54, wherein the supporting and enclosing means bonded together contains a cavity containing a partial vacuum or an inert ambient gas to facilitate the operation and reliability of the variable capacitance means.

58. The variable capacitor device of claim 54, wherein the supporting and enclosing means include continuous electrical connections through their respective layers.

59. The variable capacitor device of claim 54, wherein the LTCC material has low resistive losses at frequencies above 30 GHz.

60. The variable capacitor device of claim 55, wherein the device is electronically tunable to a selected value and wherein a predetermined actuation voltage is applied to the movable and fixed electrodes to maintain the capacitor device at the selected value.

61. The variable capacitor device of claim 54 further comprising means, bonded to the supporting means for supporting an integrated circuit for sensing and measuring the capacitance value of the variable capacitor device and apply suitable

actuation voltages to the movable and fixed electrodes to keep the capacitance of the device actively adjusted to the selected value.

62. The variable capacitor device of claim 54, wherein thin-films of materials are deposited, patterned and etched on a surface of the supporting means to form the variable capacitance means.

63. The variable capacitor device of claim 54, wherein each LTCC layer includes means for incorporating electrical connections and interconnections, through wafer vias, discrete components, sealable cavities, and bonded integrated circuits.

64. The variable capacitor device of claim 54, wherein the LTCC material has a low loss tangent and a high k factor value for high performance high-frequency applications.

65. The variable capacitor device of claim 55, wherein the variable capacitor is tuned to a selected value and a short, low-voltage, high-current pulse of sufficient duration to essentially “weld” the electrodes together at the selected capacitance value is applied.

66. The variable capacitor device of claim 55 wherein a substantially fast curing polymer material is applied to the electrodes to affix them at a desired position, whereby the device is locked into a tuned capacitance value.

67. The variable capacitor device of claim 55, wherein the electrodes are welded by a high-powered laser to a tuned position whereby the device is locked into a selected capacitance value.

68. The variable capacitor device of claim 54, wherein the supporting and enclosing means are bonded together using eutectic bonding.

69. The variable capacitor device of claim 54, wherein the supporting and enclosing means are bonded together using a glass-frit technique.

70. The variable capacitor device of claim 54, wherein the supporting and enclosing means are bonded together using a thermosetting polymer technique.

71. The variable capacitor device of claim 57, wherein the cavity provides a low-pressure, low humidity environment for the microelectromechanical device.

72. The variable capacitor device of claim 54, wherein a surface of the supporting means on which the variable capacitance means is formed is micromachined to be smooth and uniform.

73. The variable capacitor device of claim 72, wherein the surface of the supporting means is micromachined by planarizing

74. The variable capacitor device of claim 72, wherein the surface of the supporting means is micromachined by polishing.

75. The variable capacitor device of claim 62, wherein the thin-film materials are selected from the group consisting of gold, silver, platinum, and/or aluminum.

76. The variable capacitor device of claim 54, wherein the LTCC material has a dielectric constant of ( $\epsilon_r$ ) is 7.5 +/- 0.1 and a loss tangent is 0.001.

77. The variable capacitor device of claim 1, wherein the microelectromechanical device includes first and second pairs of actuation electrodes on either side of a third pair of electrodes forming a variable capacitor.

78. The variable capacitor device of claim 77, wherein each of the first and second pairs of actuation electrodes and the third pair of electrodes forming the variable capacitor includes a top electrode and a bottom electrode.

79. The variable capacitor device of claim 78, wherein each top actuation electrodes is formed on a dielectric layer that acts as a mechanical stop between such actuation electrodes and the bottom actuation electrodes.

80. The variable capacitor device of claim 78, wherein an electrostatic potential is applied to the two pair of actuation electrodes to produce an electrostatically generated force of attraction between said electrodes and cause the top activation electrodes to deflect and bend in the direction of the bottom activation electrodes, respectively, and thereby decreasing the gap between the top and bottom electrodes forming the variable capacitor.

81. The variable capacitor device of claim 78, wherein each of the pairs of activation electrodes has a gap between the top and bottom actuation electrodes greater than a gap between the top and bottom electrodes forming the variable capacitor.

82. The variable capacitor of claim 79, wherein at least one standoff is added to the dielectric layer on which the top actuation electrodes are formed, the at least one standoff preventing both the variable capacitor electrodes and the actuation electrodes from coming into contact during operation of the variable capacitor device to prevent dielectric charging or stiction.

83. The variable capacitor of claim 79, wherein at least one dimple is added to the dielectric layer on which the top actuation electrodes are formed, the at least one

dimple preventing both the variable capacitor electrodes and the actuation electrodes from coming into contact during operation of the variable capacitor device to prevent dielectric charging or stiction.

84. The variable capacitor of claim 78, further including two additional pairs of electrodes on either side of the actuator electrodes, the two additional pairs of electrodes being fused together to lock the top variable capacitor electrode in a permanently deflected position to thereby fix the variable capacitor at a selected capacitance value.

85. The variable capacitor of claim 84, wherein the two additional pairs of electrodes are fused together by a current pulse of sufficient magnitude to slightly melt and fuse each of the additional pairs of electrodes together.

86. The variable capacitor of claim 84, wherein the two additional pairs of electrodes are fused together by a pulse from a high power laser of sufficient magnitude to weld each of the additional pairs of electrodes together.

87. The variable capacitor of claim 2, wherein the upper electrode is shaped so as to create a substantially linear relationship between the applied DC voltage and the deflection of the upper electrode and thereby the capacitance between the upper and lower electrodes.

88. The variable capacitor of claim 87, wherein the upper electrode increases in width as a function of the distance from a free end of the upper electrode.

89. A variable capacitor device comprising:  
a first substrate formed from a selected material,  
a microelectromechanical device microfabricated the first substrate and comprising a variable capacitor, the microelectromechanical device including:  
first and second pairs of actuation electrodes on either side of a third pair of electrodes forming a variable capacitor, each of the first and second

pairs of actuation electrodes and the third pair of electrodes forming the variable capacitor including a movable electrode and a fixed electrode, the movable actuation electrodes being electrostatically actuated by a DC voltage applied to said movable actuation electrodes to vary the capacitance between the movable electrode and the fixed electrode forming the variable capacitor, and a second multi-layered substrate formed from the selected material, a portion of the second substrate being removed to form a cavity therein, the first and second substrates being bonded together to enclose the microelectromechanical device.

90. The variable capacitor device of claim 89, wherein each movable actuation electrodes is formed on a dielectric layer that acts as a mechanical stop between such actuation electrodes and the bottom actuation electrodes.

91. The variable capacitor device of claim 89, wherein an electrostatic potential is applied to the two pair of actuation electrodes to produce an electrostatically generated force of attraction between said actuation electrodes and cause the top actuation electrodes to deflect and bend in the direction of the bottom actuation electrodes, respectively, and thereby decreasing the gap between the top and bottom electrodes forming the variable capacitor.

92. The variable capacitor device of claim 89, wherein each of the pairs of actuation electrodes has a gap between the top and bottom actuation electrodes greater than a gap between the top and bottom electrodes forming the variable capacitor.

93. The variable capacitor of claim 90, wherein at least one standoff is added to the dielectric layer on which the top actuation electrodes are formed, the at least one standoff preventing both the variable capacitor electrodes and the actuation electrodes from coming into contact during operation of the variable capacitor device to prevent dielectric charging or stiction.

94. The variable capacitor of claim 90, wherein at least one dimple is added to the dielectric layer on which the top actuation electrodes are formed, the at least one dimple preventing both the variable capacitor electrodes and the actuation electrodes from coming into contact during operation of the variable capacitor device to prevent dielectric charging or stiction.

95. The variable capacitor of claim 89, further including two additional pairs of electrodes on either side of the actuation electrodes, the two additional pairs of electrodes being fused together to lock the movable variable capacitor electrode in a permanently deflected position to thereby fix the variable capacitor at a selected capacitance value.

96. The variable capacitor of claim 95, wherein the two additional pairs of electrodes are fused together by a current pulse of sufficient magnitude to slightly melt and fuse each of the additional pairs of electrodes together.

97. The variable capacitor of claim 95, wherein the two additional pairs of electrodes are fused together by a pulse from a high power laser of sufficient magnitude to weld each of the additional pairs of electrodes together.

98. The variable capacitor of claim 2, wherein the upper electrode is shaped so as to create a substantially linear relationship between the applied DC voltage and the deflection of the upper electrode and thereby the capacitance between the upper and lower electrodes.

99. The variable capacitor of claim 89, wherein the upper electrode forming the variable capacitor is shaped so as to create a substantially linear relationship between the applied DC voltage and the deflection of said upper electrode and thereby the capacitance between the upper and lower electrodes forming the variable capacitor.



100. The variable capacitor of claim 94, wherein the first and second substrates are formed from multiple layers of low temperature co-fired ceramic.

101. The variable capacitor of claim 95, wherein the first and second substrates are formed from multiple layers of low temperature co-fired ceramic.

102. The variable capacitor device of claim 90, wherein an increased amount of area of the variable capacitor movable electrode is brought into contact with the mechanical stop in a zipper-like motion as the applied DC voltage is increased, whereby the capacitance between said movable electrode and the variable capacitor fixed electrode is varied as the amount of area of said movable electrode contacting the mechanical stop is varied.